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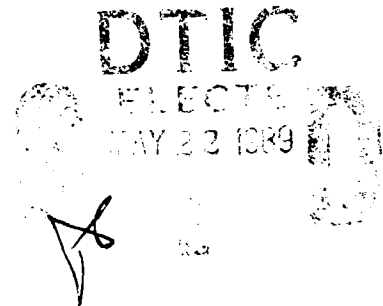
COMPARISON OF PEEL AND LAP SHEAR BOND STRENGTHS
FOR ELASTIC JOINTS WITH AND WITHOUT RESIDUAL STRESSES

by

A. N. Gent and C.-W. Lin

Institute of Polymer Science
The University of Akron
Akron, Ohio 44325

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Fracture energies have been calculated from peel and lap shear experiments on rubber strips bonded together with a pressure ⁰ sensitive acrylic adhesive layer. In some cases, one strip was held stretched during bonding, to create joints with built-in stresses. Good agreement was obtained in all cases. →		

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provided that elastic strain energy was taken into account, the work of detachment being about 180 J/m^2 ^{sq. m.} For thick rubber layers, about 3 - 4 mm. or greater, the strain induced by peel or shear forces was rather small and the assumption of linear elastic behavior was found to be satisfactory. Good agreement was then obtained with the relations derived by Kendall (1,2).

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1. Introduction

Peel and lap shear tests are simple and widely-used methods of measuring the strength of an adhesive bond. But the results are not easily compared. The peel force per unit width of the joint can be directly interpreted as an energy G_a required to bring about separation per unit area of interface. On the other hand, it is usual to describe the strength of a lap shear joint by the mean shear stress causing fracture. But the joint does not fail in shear by simultaneous rupture of the entire bonded area. Instead, the bond fails first at a highly stressed site, usually at one edge, and failure then spreads across the interface.

Kendall calculated the strength of a lap-shear joint on this basis (1,2), using Griffith's energy-balance approach, and showed that the fracture energy deduced from lap shear measurements on model joints agreed well with that given by a simple peeling experiment. However, Kendall assumed that the stress-strain relationship in tension for the two adhering layers was a linear one and the strains were small. These assumptions are not necessarily true for thin layers, which might be stretched to large strains during bonding or detachment. The theory is reviewed here and measurements on extensible rubber layers are compared with predictions made with and without the assumption of small strains.

If one of the adherends is stretched when it is bonded to the other, the joint is made more resistant to separation, at least for prestrains below a critical level at which the layers spontaneously

separate on release. Both the strengthening effect of initial prestrains and the critical degree of prestrain at which spontaneous delamination occurs can be calculated on the basis of elastic strain energy contributions to the work of separation, assuming that the intrinsic strength of adhesion is unchanged by prestretching. Some measurements are reported of the peel and lap shear strengths of joints prepared by bonding a stretched rubber strip to an unstretched one. Such joints can be regarded as models of adhesive joints prestressed due to a variety of causes; for example, by shrinkage of one layer on setting or by differential thermal contraction.

2. Theoretical Considerations

Work is expended in two ways in peeling. First, the detached strip is stretched, to a strain of \underline{e} , say, requiring input of strain energy \underline{U} per unit volume. If it was already stretched to a strain of \underline{e}^* in the bonded state, before detachment, with a corresponding amount of strain energy \underline{U}^* per unit volume stored in it, then the additional energy supplied is $\underline{U} - \underline{U}^*$. Secondly, an amount of energy \underline{G}_a is expended per unit area of interface in separating the adhering surfaces. (It is assumed that \underline{G}_a is the same for stretched and unstretched adhering surfaces, but we note that unit area of surface becomes $(1 + \underline{e}^*)^{1/2}$ in the stretched state.) Thus, the work done by the peel force \underline{F} during detachment of a strip of unit length in the unstrained state (given by $\underline{F}\underline{x}$ where \underline{x} is the displacement of the point of application of the force) is equal to the sum of these two terms,

$$F x = [G_a(1 + e^*)^{1/2} + (U - U^*)t]w \quad (1)$$

where \underline{t} is the unstrained thickness and \underline{w} the unstrained width of the detaching layer.

From geometrical considerations (Figure 1) \underline{x} is given by

$$x = [1 + e - (1 + e^*)\cos \theta] \quad (2)$$

where θ is the peel angle. The fracture energy G_a is then obtained from Equations 1 and 2,

$$G_a(1 + e^*)^{1/2} = (F/w)[1 + e - (1 + e^*)\cos \theta] - (U - U^*)t. \quad (3)$$

In the case of linear elasticity, the strains \underline{e} and \underline{e}^* are given by F/wtE and F^*/wtE , where E is the tensile (Young) modulus of the strips, F^* is the residual tension in the strip before separation, corresponding to the strain \underline{e}^* , and the strain energies \underline{U} and \underline{U}^* are given by $(F/wt)^2/2E$ and $(F^*/wt)^2/2E$. Thus, for peeling a linearly-elastic strip, the fracture energy is given by

$$G_a(1 + e^*)^{1/2} = (F/w)[1 - (1 + e^*)\cos \theta] + (F^2 + F^{*2})/2w^2tE. \quad (4)$$

If the strip is not prestressed, $\underline{e}^* = F^* = U^* = 0$, and Equations 3 and 4 become

$$G_a = (F/w)[1 + e - \cos \theta] - Ut \quad (5)$$

and

$$G_a = (F/w)[1 - \cos \theta] + F^2/2w^2tE. \quad (6)$$

If the strip is relatively inextensible, the second term in Equations 5 and 6 is negligibly small in comparison with the first, unless θ is close to zero. The relation for the fracture energy then takes its simplest form

$$G_a = (F/w)[1 - \cos \theta]. \quad (7)$$

For lap shear debonding, $\theta = 0$ in Equation 3. Considering only one layer of the sandwich to be extensible, the fracture energy can be expressed as:

$$G_a(1 + e^*)^{1/2} = (F/w)(e - e^*) - (U - U^*)t \quad (8)$$

Again, if it is assumed that the layer is linearly-elastic, this relation becomes

$$G_a(1 + e^*)^{1/2} = (F - F^*)^2 / 2w^2tE. \quad (9)$$

And if the layer was not prestressed at the time the joint was made, $e^* = F^* = 0$, and

$$G_a = F^2 / 2w^2tE. \quad (10)$$

When two strips are pulled apart, Figure 2, with strain energy imparted to both, then Equation 8 becomes

$$G_a(1 + e^*)^{1/2} = (F/w)(e - e_2) - [U - U_{e_2} - (1 + e^*)U_{e_1}]t \quad (11)$$

where e_2 denotes the strain in the bonded portion of the prestressed strip during detachment and e_1 denotes the corresponding strain in the other strip, Figure 3. They are related to the prestrain e^* at the time of bonding and to the detachment force F by the relations

$$e_2 = e^* + (1 + e^*)e_1 \quad (12)$$

and

$$F = F_1 + F_2 \quad (13)$$

where F_1 and F_2 are the tensile forces in the two bonded strips.

For linearly-elastic strips, Equation 11 becomes

$$G_a(1 + e^*)^{1/2} = (F - F^*)^2 / 2(2 + e^*)w^2tE. \quad (14)$$

When the prestrain e^* is zero, $e_1 = e_2$, $F_1 = F_2$, and $U_{e_1} = U_{e_2}$.

Equations 11 and 14 then become

$$G_a = (F/w)(e - e_1) - (U - 2U_{e_1})t \quad (15)$$

$$G_a = (F/w)^2/4tE. \quad (16)$$

The above relations for fracture force based on linear elastic behavior (Equations 9 and 14) were originally derived by Kendall (3) with e^* assumed to be much smaller than unity. He pointed out that the detachment force F increased linearly with the magnitude of the preload F^* , up to a value of F^* equal to the original failure force. For values of F^* of this amount or greater, detachment will occur spontaneously on releasing the joint from the force F^* applied during bonding.

We now compare the predictions of these various relations with experimental measurements of the forces required to detach soft rubber layers, adhering together.

3. Experimental Details

Sheets of vulcanized rubber having a wide range of thickness were prepared using the mix recipe and vulcanization conditions given in the Appendix. Experimental relations between tensile stress and elongation e , and between elastic strain energy U per unit volume and e , are shown in Figures 4 and 5. Strips about 20 mm wide and 200 mm long were cut from the rubber sheets and coated with a thin layer, about 0.2 mm thick, of an acrylic adhesive emulsion (Monsanto Gelva Multipolymer Resin Emulsion RA-2397, kindly supplied by Mr. J. M. Questel, Adhesive Consultants, Inc., Akron, Ohio). After drying in an air oven at 50°C for 2 h, two similar coated rubber

strips were pressed into contact to form a model joint.

Measurements of peel force and lap shear failure force were made at the same rate of propagation of the debond, about 0.1 mm/sec. In peeling, one rubber layer was bonded to a steel plate and the other layer was peeled away from it at an angle of 45° , Figure 1. Lap shear measurements were carried out symmetrically, as shown in Figure 2.

The experiments were carried out at room temperature, about 25°C .

4. Experimental Results and Discussion

(i) Joints prepared without a prestress

(a) Peel strength

The measured peel forces and lap shear failure forces are given in Tables 1 and 2 for rubber layers having thicknesses ranging from 0.6 to 12 mm. Values of fracture energy were calculated from the peel forces, using three different assumptions: that the layers were inextensible (Equation 7), that they were extensible but linearly elastic (Equation 6), and that they were non-linearly elastic (Equation 5). The results are plotted in Figure 6 against the thickness of the rubber layer being peeled away. As can be seen, the results calculated assuming zero extension or assuming linear elasticity are not constant. Values obtained with thin rubber layers are considerably smaller than those from thick layers. On the other hand, values calculated taking into account the non-linearly elastic character of rubber are constant over the whole thickness range. We

rubber strips for various amounts of prestrain \underline{e}^* . When the strips were assumed to be linearly-elastic the results were not constant but depended on the strip thickness, especially for thin strips. On the other hand, when non-linearly elastic behavior of the strips was taken into account, then the calculated values were approximately constant, independent of the strip thickness. Moreover, the average value, about 210 J/m^2 , was close to that obtained from peeling and lap shear measurements on unstressed joints, Figures 6 and 7.

(b) Lap shear strength

In order to calculate fracture energy for prestressed lap shear joints in the most general case, Equation 11, it is necessary to deduce the strains \underline{e}_1 and \underline{e}_2 in the two bonded strips under the failure force \underline{F} . This was done by trial and error, using Equations 12 and 13. Values obtained in this way are given in Table 4, together with the results for \underline{G}_a calculated from them. As can be seen in Figure 9, these values of \underline{G}_a are approximately constant at about $160 \pm 20 \text{ J/m}^2$, close to the value deduced from peeling measurements, and independent of the strip thickness, whereas values calculated on the basis of linearly elastic behavior using Equation 14 are much smaller for thin strips and not independent of the strip thickness. We conclude that it is necessary to take into account non-linear elastic behavior of rubber strips to predict the effect of large prestrains on peel and lap shear strengths.

(c) Strengthening effect of prestresses

As shown by the failure forces given in Tables 3 and 4,

conclude that it is necessary to employ the accurate non-linear relationship, Equation 5, in order to obtain correct values for the fracture energy from peeling experiments with unreinforced rubber strips, even when the thickness is 3 mm or more.

(b) Lap shear strength

Values of fracture energy calculated from lap shear measurements are plotted in Figure 7. Again, results obtained assuming linear elasticity are found to depend upon the thickness of the adhering rubber layers up to about 8 mm. When a non-linear relation is used to deduce the fracture energy, the results become constant over the whole thickness range, and they agree well with the corresponding value obtained from peeling measurements, about 180 J/m^2 .

We conclude that the present well-bonded rubber layers stretch too much in peeling and lap shear measurements for the elementary theory of fracture based on linear elasticity to apply. Instead it is necessary to take into account non-linear behavior in tension to obtain accurate values of the work of detachment.

(ii) Joints prepared with a prestress

(a) Peel strength

Peel forces for prestressed joints prepared using strips of a wide range of thickness are given in Table 3, with values of fracture energy G_a calculated from them assuming that the strips were linearly elastic, Equation 4, or that they were non-linearly elastic, Equation 3. The results are plotted in Figure 8 against the thickness of the

rubber strips for various amounts of prestrain \underline{e}^* . When the strips were assumed to be linearly-elastic the results were not constant but depended on the strip thickness, especially for thin strips. On the other hand, when non-linearly elastic behavior of the strips was taken into account, then the calculated values were approximately constant, independent of the strip thickness. Moreover, the average value, about 210 J/m^2 , was close to that obtained from peeling and lap shear measurements on unstressed joints, Figures 6 and 7.

(b) Lap shear strength

In order to calculate fracture energy for prestressed lap shear joints in the most general case, Equation 11, it is necessary to deduce the strains \underline{e}_1 and \underline{e}_2 in the two bonded strips under the failure force \underline{F} . This was done by trial and error, using Equations 12 and 13. Values obtained in this way are given in Table 4, together with the results for \underline{G}_a calculated from them. As can be seen in Figure 9, these values of \underline{G}_a are approximately constant at about $160 \pm 20 \text{ J/m}^2$, close to the value deduced from peeling measurements, and independent of the strip thickness, whereas values calculated on the basis of linearly elastic behavior using Equation 14 are much smaller for thin strips and not independent of the strip thickness. We conclude that it is necessary to take into account non-linear elastic behavior of rubber strips to predict the effect of large prestrains on peel and lap shear strengths.

(c) Strengthening effect of prestresses

As shown by the failure forces given in Tables 3 and 4,

prestressed joints were more resistant to separation than non-prestressed joints. The maximum increase in strength was about 50 percent. But, at a critical amount of prestrain, denoted in Table 4 by e_c^* , the joints spontaneously separated on releasing them from the prestress. Values of fracture energy have been calculated from the corresponding pre-tension forces F_c^* , using Equation 11. They are included in Table 4. They are seen to be in good agreement with values determined directly from measurements of failure forces. Thus, the maximum amount of prestress that a joint can withstand is also given correctly by fracture energy considerations.

5. Conclusions

Peel and lap shear debonding forces are related by a common failure criterion: that a critical amount of energy G_a is needed for debonding. This conclusion of Kendall has been verified again for adhering rubber strips of a wide range of thickness, bonded together with various amounts of residual stress. But it has proved necessary to take into account both the relatively large strains that rubber can undergo during detachment, especially when the strips are thin, and the non-linear elastic response of rubber. Otherwise, the inferred fracture energies are too small, by factors of up to 3 or 4 in the present experiments.

Acknowledgements

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Appendix

Mix formulation in parts by weight and vulcanization conditions were as follows: natural rubber, 100; zinc oxide, 5; stearic acid, 2; accelerator (Santocure), 1; sulfur, 2.5. Vulcanization was effected by heating for 30 min. at 150°C.

Table 1 : Peeling Results

Strip	Failure	Elongation	Fracture energy G_a [J/m^2]		
thickness	force		calc. from		
t [mm]	F [N]	e	(Eq. 7)	(Eq. 6)	(Eq. 5)
0.64	6.1	0.71	89	145	182
0.91	6.9	0.57	100	154	193
1.23	9.4	0.77	138	163	175
2.10	10.2	0.27	150	179	195
4.31	12.2	0.28	180	186	188

Table 2: Lap Shear Results

Strip	Failure	Elongation	Fracture energy G_a [J/m^2]	
thickness	force		calc. from	
t [mm]	F [N]	e	(Eq. 16)	(Eq. 15)
0.58	9.6	1.42	100	175
0.88	12.5	0.92	112	173
2.10	21.5	0.77	138	189
4.30	32.4	0.57	153	169
12.50	58.1	0.25	169	172

Table 3: Peeling Forces for Pre-stressed Joints

Strip	Prestrain	Preload	Failure	Fracture energy G_a [J/m^2]	
thickness			force	calc. from	
t [mm]	e^*	F^* [N]	F [N]	(Eq. 4)	(Eq. 3)
0.85	0.25	3.7	7.9	126	184
	0.30	4.3	9.0	142	195
	0.60	6.6	12.0	169	239
1.20	0.25	5.3	10.3	155	189
	0.30	5.9	11.9	181	218
	0.60	9.2	15.2	202	247
2.10	0.25	9.2	13.6	188	215
	0.30	10.5	15.9	217	234
4.30	0.10	6.2	12.4	183	200

Table 4: Lap Shear Failure Forces for Pre-stressed Joints

Strip thickness t [mm]	Pre- strain e^*	Failure strains		Failure forces [N]			Fracture energy G_a [J/m ²]	
		e_1	e_2	F	F_1	F_2	calc. from	
							(Eq. 14)	(Eq. 11)
		(calc.)		(meas.)	(calc.)			
0.85	0.25	0.44	0.80	13.2	5.5	7.7	53	139
	0.30	0.50	0.95	14.6	6.1	8.5	56	127
	0.60	0.55	1.48	17.9	6.4	11.5	69	171
	0.80 ^a							202 ^b
1.25	0.25	0.48	0.85	20.1	8.6	11.5	91	135
	0.30	0.61	1.09	23.6	9.9	13.7	128	189
	0.65 ^a							209 ^b
2.10	0.25	0.42	0.78	31.9	13.1	18.8	128	129
	0.30	0.45	0.89	34.0	13.8	20.2	132	192
	0.45 ^a							209 ^b
4.30	0.10	0.22	0.34	40.7	16.9	23.8	155	191
	0.25 ^a							162 ^b

a: prestrain e_c^* causing spontaneous debonding on release.

b: calculated from Eq. 11, putting $F = e = U = 0$; $U_{e_2} + (1 + e^*) U_{e_1} = U^*$.

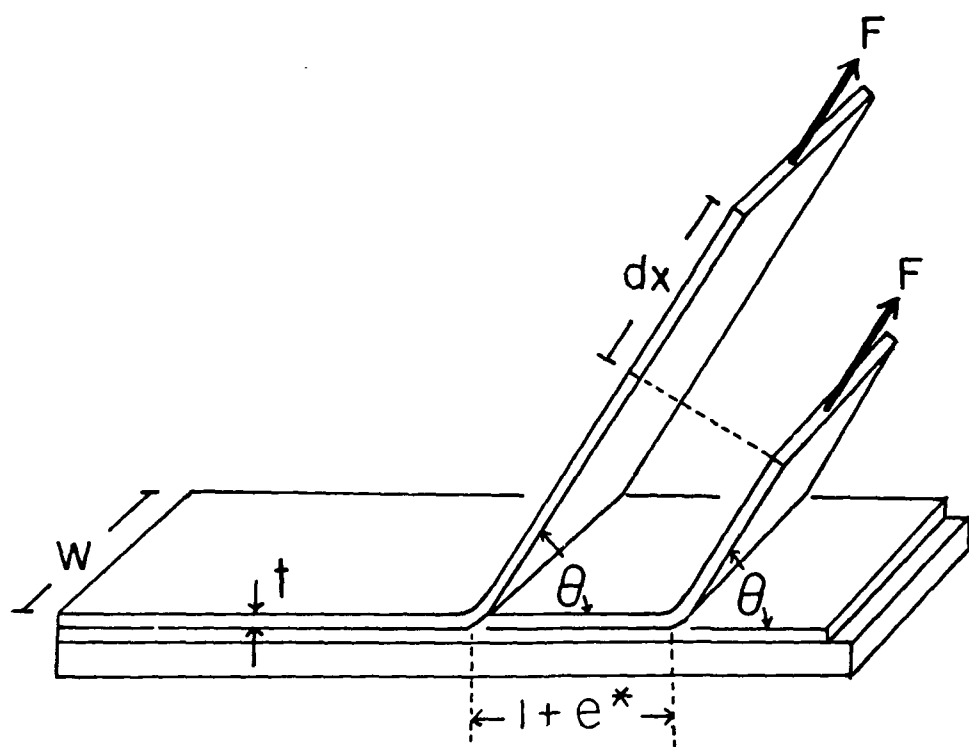


Figure 1

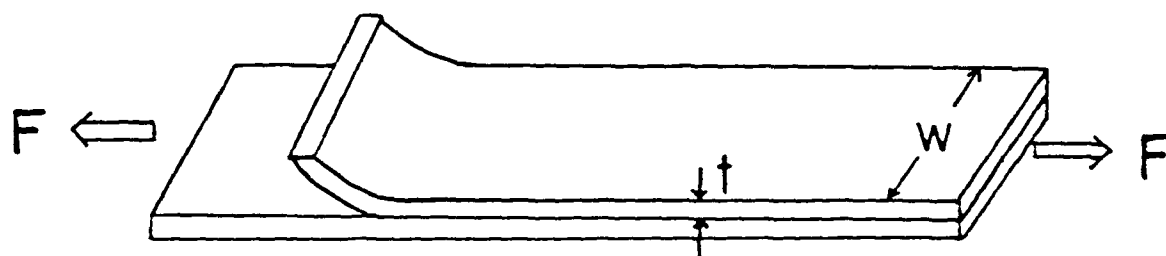
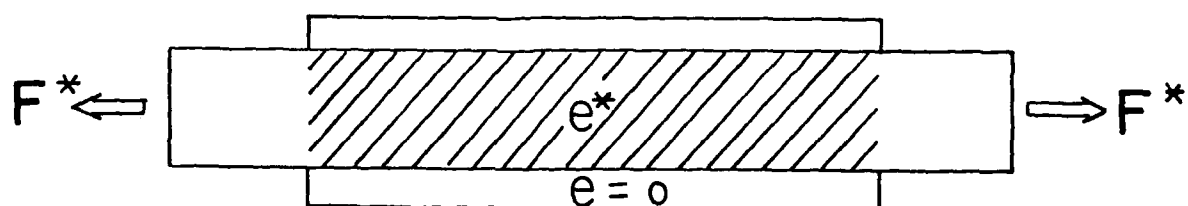
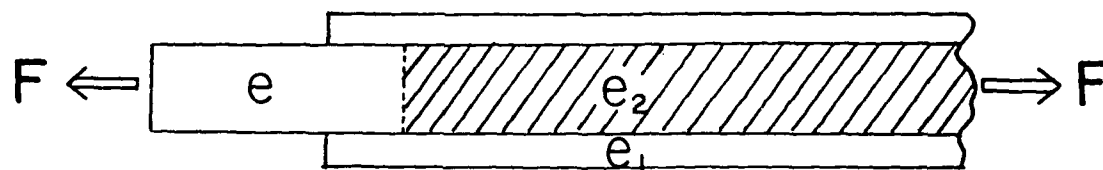


Figure 2



(a)



(b)

Figure 3

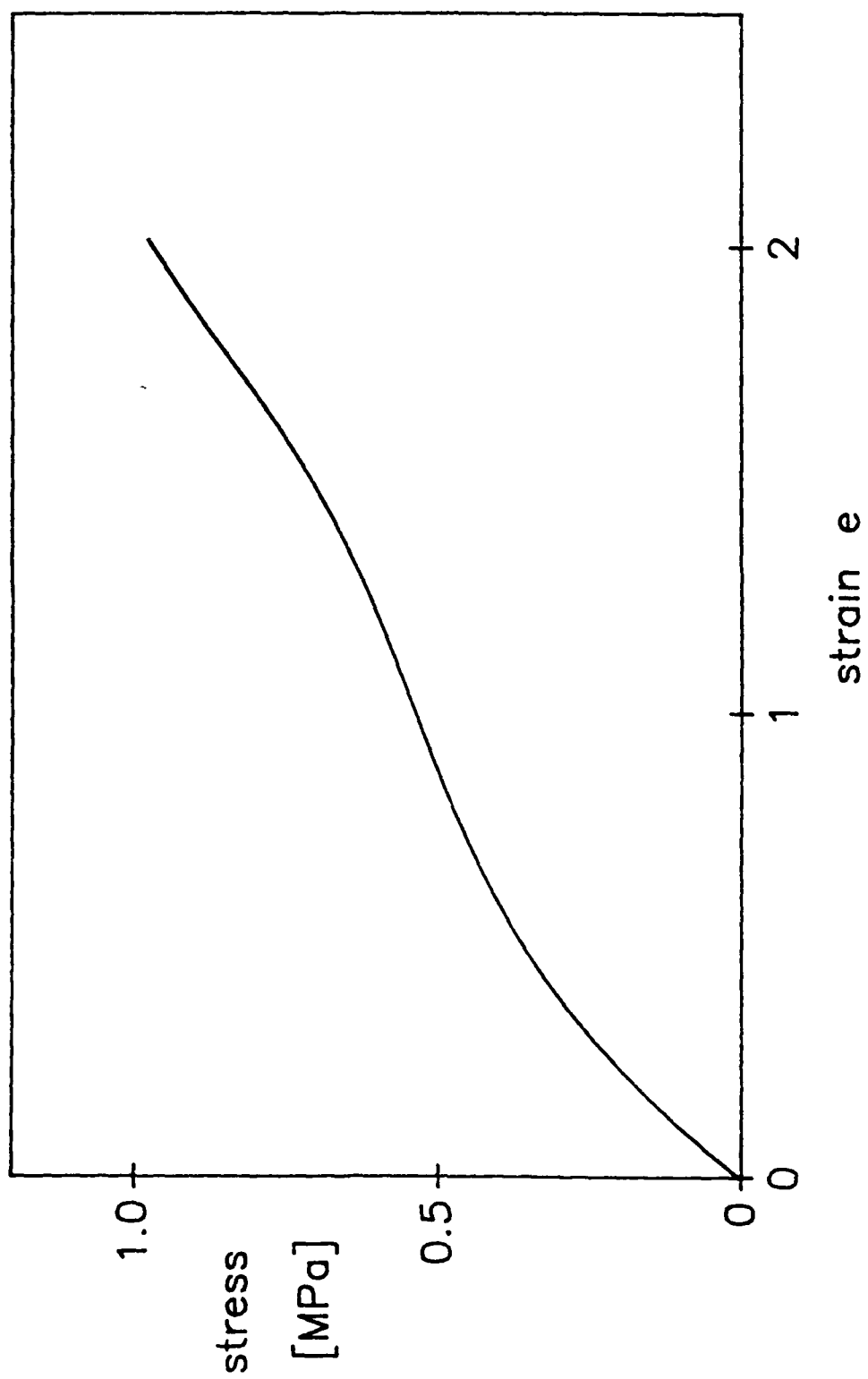
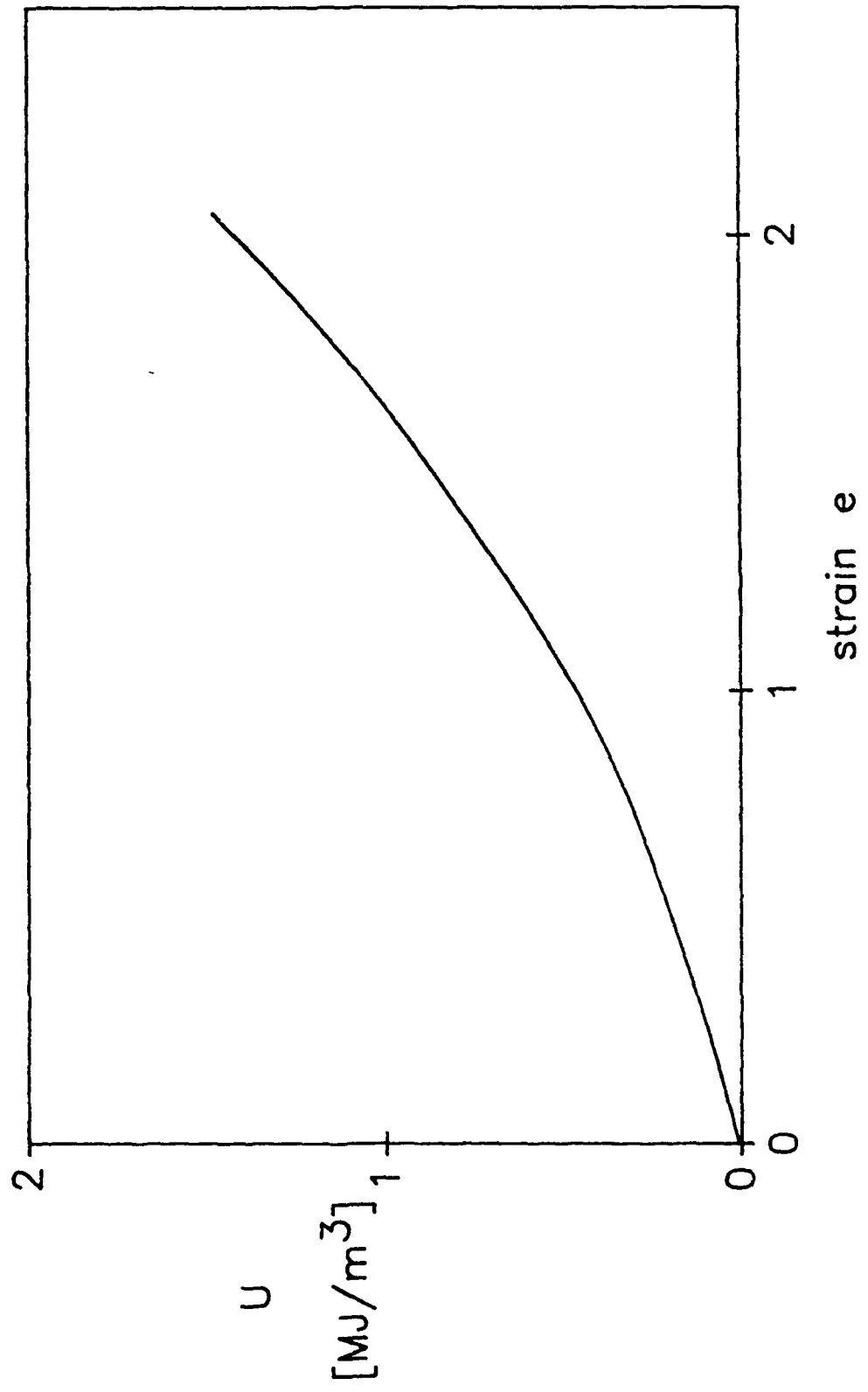


Figure 4

Figure 5

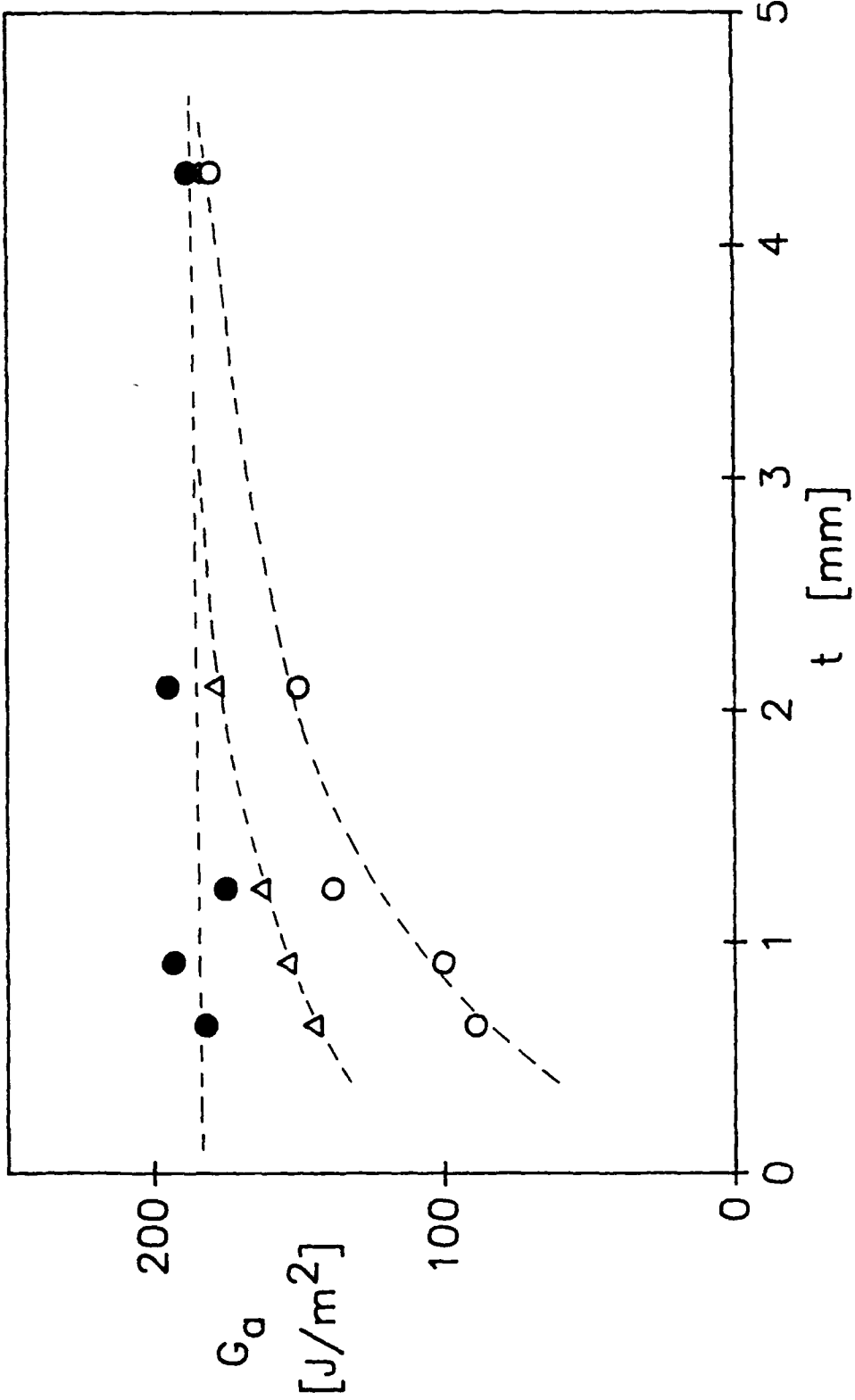


Figure 6

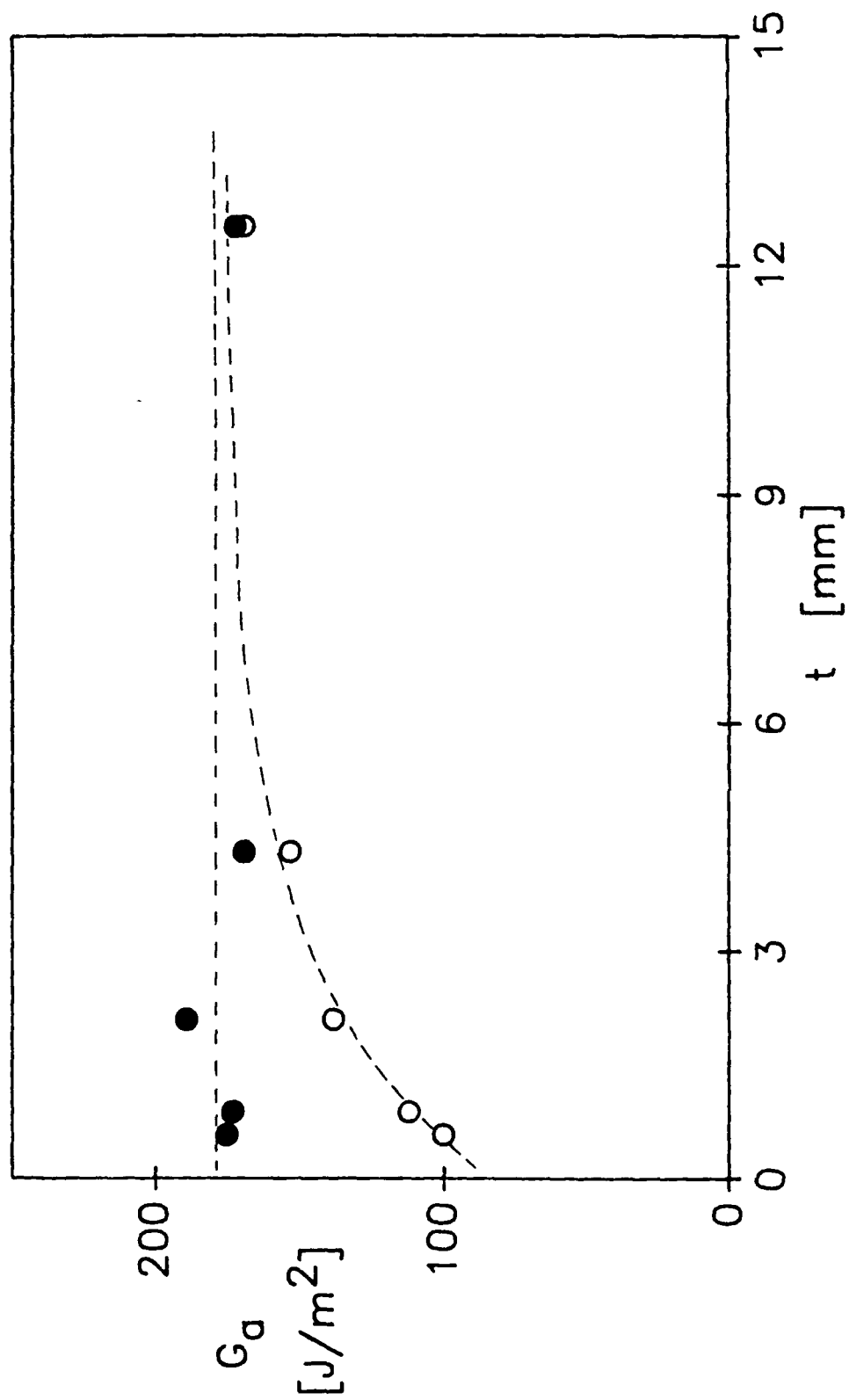


Figure 7

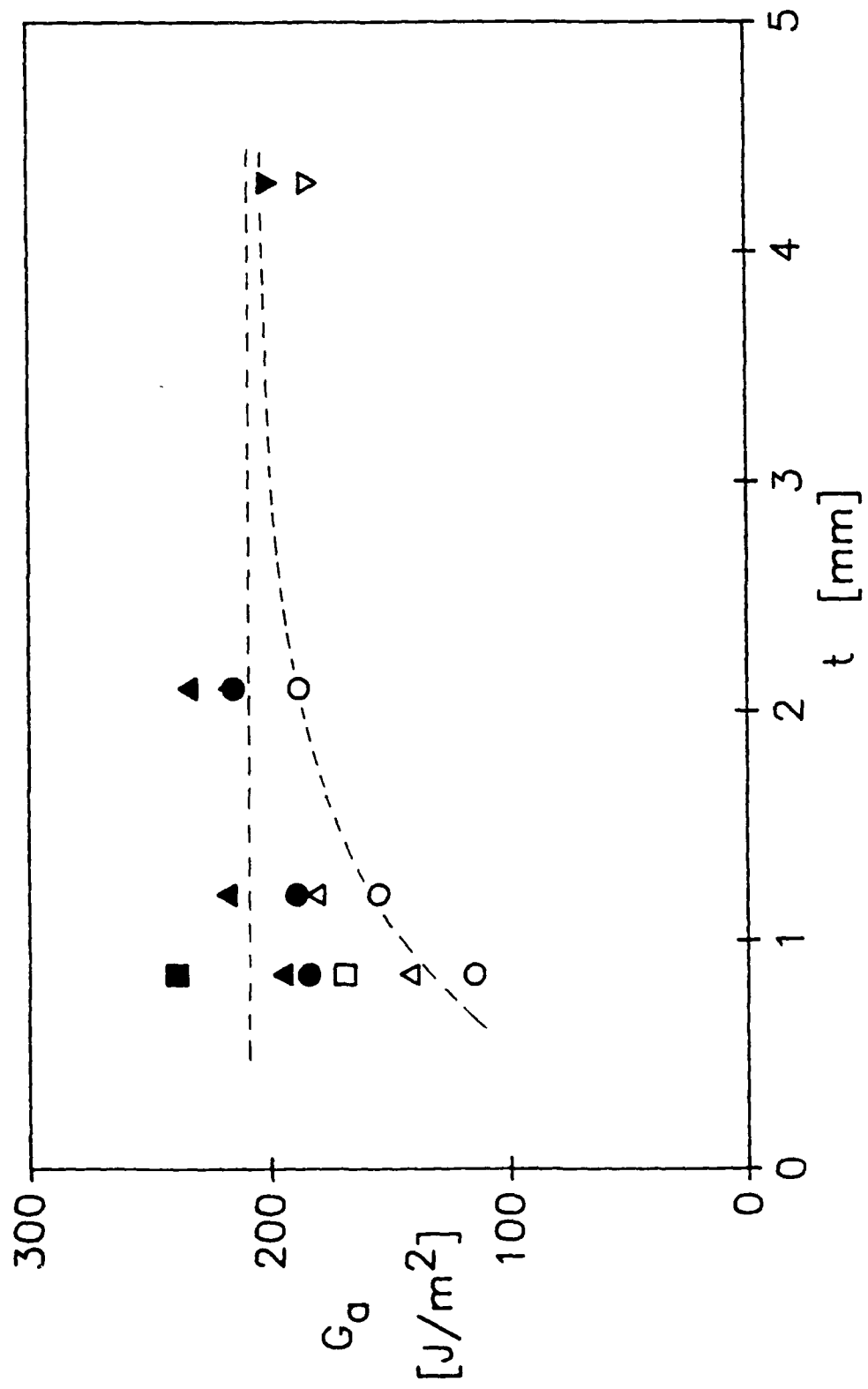


Figure 8

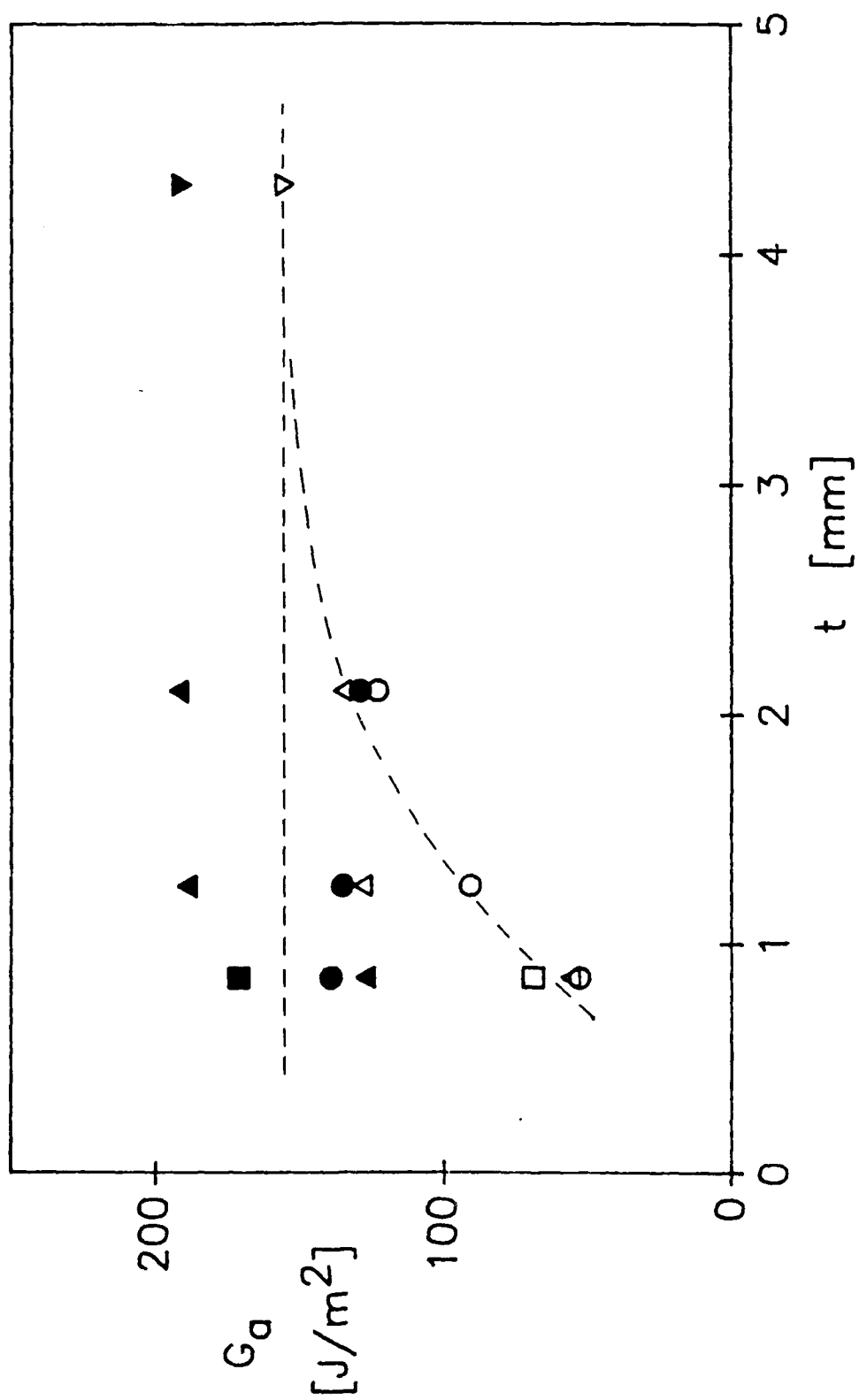


Figure 9

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Shreveport, Louisiana 71130

Dr. J.R. West
Morton Thiokol, Inc.
P.O. Box 30058
Shreveport, Louisiana 71130

Dr. D.D. Dillehay
Morton Thiokol, Inc.
Longhorn Division
Marshall, TX 75670

G.T. Bowman
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Prof. J.T. Dickinson
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Pullman, WA 99164-2814

M.H. Miles
Dept. of Physics
Washington State University
Pullman, WA 99164-2814

Dr. T.F. Davidson
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Morton Thiokol, Inc.
Aerospace Group
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Ogden, UT 84405

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Naval Sea Systems Command
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NAVSEA-62R2
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Washington, DC 20362

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Naval Sea Systems Command
SEA 64E
Washington, DC 20362

Brian Wheatley
Atlantic Research Corp.
7511 Wellington Road
Gainesville, VA 22065

Mr. G. Edwards
Naval Sea Systems Command
Code 62R32
Washington, DC 20362

C. Dickinson
Naval Surface Weapons Center
White Oak, Code R-13
Silver Spring, MD 20910

Prof. John Deutch
MIT
Department of Chemistry
Cambridge, MA 02139

Dr. E.H. deButts
Hercules Aerospace Co.
P.O. Box 27408
Salt Lake City, UT 84127

David A. Flanigan
Director, Advanced Technology
Morton Thiokol, Inc.
Aerospace Group
3340 Airport Rd.
Ogden, UT 84405

Dr. L.H. Caveny
Air Force Office of Scientific
Research
Directorate of Aerospace Sciences
Bolling Air Force Base
Washington, DC 20332

W.G. Roger
Code 5253
Naval Ordnance Station
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Dr. L. Rothstein
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Naval Explosives Dev. Engineering Dept.
Naval Weapons Station
Yorktown, VA 23691

Dr. M.J. Kamlet
Naval Surface Weapons Center
Code R11
White Oak, Silver Spring, MD 20910

Dr. Henry Webster, III
Manager, Chemical Sciences Branch
ATTN: Code 5063
Crane, IN 47522

Dr. A.L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Code RD-1
Washington, DC 20380

Dr. H.G. Adolph
Naval Surface Weapons Center
Code R11
White Oak
Silver Spring, MD 20910

U.S. Army Research Office
Chemical & Biological Sciences
Division
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Research Triangle Park, NC 27709

Dr. John S. Wilkes, Jr.
FJSRL/NC
USAF Academy, CO 80840

Dr. H. Rosenwasser
AIR-320R
Naval Air Systems Command
Washington, DC 20361

Dr. Joyce J. Kaufman
The Johns Hopkins University
Department of Chemistry
Baltimore, MD 21218

Dr. A. Nielsen
Naval Weapons Center
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Los Alamos, NM 87544

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Institute Polymer Science
University of Akron
Akron, OH 44325

Dr. D.A. Shockey
SRI International
333 Ravenswood Ave.
Menlo Park, CA 94025

Dr. R.B. Kruse
Morton Thiokol, Inc.
Huntsville Division
Huntsville, AL 35807-7501

G. Butcher
Hercules, Inc.
P.O. Box 98
Magna, UT 84044

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7511 Wellington Road
Gainesville, VA 22065

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White Oak
Silver Spring, MD 20910

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Georgia Institute of Tech.
School of Aerospace Engineering
Atlanta, GA 30332

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Indian Head, MD 20640

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University of Maryland
Dept. of Mechanical Engineering
College Park, MD 20742

Herb Richter
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China Lake, CA 93555

J.T. Rosenberg
SRI International
333 Ravenswood Ave.
Menlo Park, CA 94025

G.A. Zimmerman
Aerojet Tactical Systems
P.O. Box 13400
Sacramento, CA 95813

Prof. Kenneth Kuo
Pennsylvania State University
Dept. of Mechanical Engineering
University Park, PA 16802

T.L. Boggs
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Strategic Systems Program Office
Crystal Mall #3, RM 1048
Washington, DC 23076

R.G. Rosemeier
Brimrose Corporation
7720 Belair Road
Baltimore, MD 20742

C. Gotzmer
Naval Surface Weapons Center
Code R-11
White Oak
Silver Spring, MD 20910

G.A. Lo
3251 Hanover Street
B204 Lockheed Palo Alto Research Lab
Palo Alto, CA 94304

R.A. Schapery
Civil Engineering Department
Texas A&M University
College Station, TX 77843

Dr. Y. Gupta
Washington State University
Department of Physics
Pullman, WA 99163

J.M. Culver
Strategic Systems Projects Office
SSPO/SP-2731
Crystal Mall #3, RM 1048
Washington, DC 20376

Prof. G.D. Duvall
Washington State University
Department of Physics
Pullman, WA 99163

Dr. E. Martin
Naval Weapons Center
Code 3858
China Lake, CA 93555

Dr. M. Farber
135 W. Maple Avenue
Monrovia, CA 91016

W.L. Elban
Naval Surface Weapons Center
White Oak, Bldg. 343
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